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Development and validation of a dynamic primary standard for unsteady liquid flow calibration

Florestan Ogheard [a,*], Jean Noël [a], Pascal Granger [a], Carl-André Gassette [b]

[a] Centre Technique des Industries Aérauliques et Thermiques, Villeurbanne, France
[b] Institut National des Sciences Appliquées, Villeurbanne, France

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ABSTRACT

LNE-CETIAT liquid flow laboratory is the French Designated Institute for liquid water flow rate from 1 g h^{-1} to 50 t h^{-1}. Historically, its primary standards are based on the flying start and stop gravimetric method. The best relative expanded uncertainty for liquid mass flow rate is 0.05% ($k = 2$). In the scope of the Joint Research Project Metrowamet and its mission to maintain and develop the French standards for liquid flow, LNE-CETIAT has developed and validated a dynamic primary standard for unsteady liquid flow calibration. This paper will first present the developped system, which is composed of a dynamic flow generator and a dedicated measuring system together with its own software for data acquisition and processing. The validation, realized by intra and inter-laboratory comparisons for static and dynamic flows, is presented in the third chapter. Finally, the validation of the measurement and calibration capabilities, based on internal tests and inter-laboratory comparisons are presented.

1. Introduction

LNE-CETIAT's liquid flow laboratory is the French Designated Institute (DI) for the realization and dissemination of the liquid (water) flow units such as mass flow, volume flow, and totalized mass and volume. The main missions of LNE-CETIAT's liquid flow laboratory are the calibration of flow and water meters, studies, research & development and trainings. In addition, the laboratory designs and develops its own calibration and test methods, either on its own funds or as part of European and national research projects in metrology.

Historically, LNE-CETIAT primary standards for liquid flow are based on the flying start and stop gravimetric method, covering a range of 1 g h^{-1} to 50 t.h^{-1}with a best relative expanded uncertainty of 0.05% ($k = 2$). Fig. 1 presents a schematic of LNE-CETIAT primary standard for macro flow rates.

For several years, the "historic" laboratory has experienced significant commercial activity (calibrations and tests for customers). This priority activity immobilizes the reference bench and slows down the tests for the development of the laboratory. In this context, LNE and CETIAT have decided to invest in order to create a test and calibration bench dedicated to the research and development of new methods.

In addition, the practical use of flowmeters and water meters by users increasingly differs from the ideal conditions under which calibrations are performed in the laboratory. For example, most flowmeters are calibrated for static flow rates, i.e. when the flow rate is stable and regulated at a constant value, whereas they are used to measure variable flow rates more or less quickly. In this case, the non-negligible response time of the flowmeter induces a measurement bias not estimated by current static calibration methods, but potentially having an impact in the case of dosing applications for pharmaceutical liquids, for example.

This problem of metrological representativeness therefore requires the development of new methods allowing calibrations to be carried out under realistic conditions, while keeping the measurement uncertainty as low as possible, and without increasing the calibration times, or even reducing them in order to respond to growing market activity.

Starting in June 2018, LNE-CETIAT is an active member of the Joint Research Project Metrowamet consortium, which aims to develop and validates dynamic primary standards for water meters [1].

In [2], the Metrowamet consortium partners, which includes National Metrology Institutes and Designated Institutes for liquid flow, took part of a first inter-laboratory comparison for unsteady flow profiles. This flow profiles have been conceived to be statistically representative of a real-world domestic water consumption profile, as presented in Fig. 2.

* Corresponding author.
E-mail address: florestan.ogheard@cetiat.fr (F. Ogheard).

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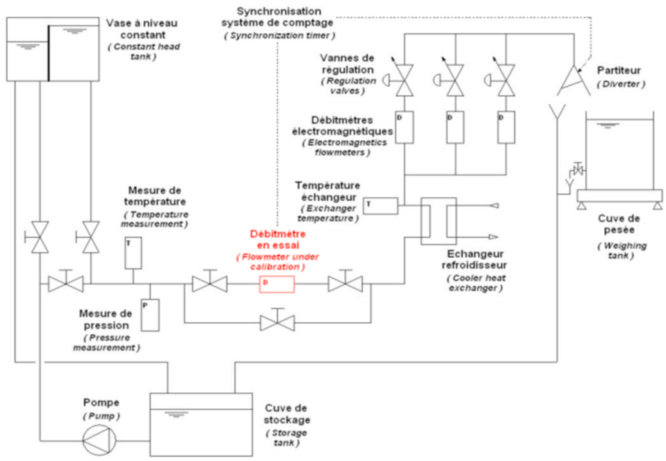


Fig. 1. Schematic of LNE-CETIAT primary standard for macro flow rates.

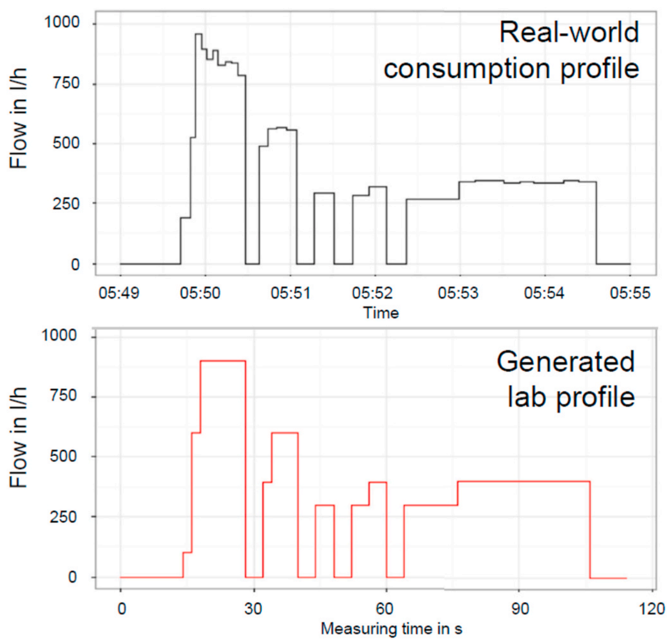


Fig. 2. Real world consumption profile and generated lab dynamic flow profile.

In order to answer the upcoming needs, a new method of calibration under dynamic conditions (in terms of fluctuations of physical influence quantities) of flow, temperature and pressure, has been developed at LNE-CETIAT's liquid flow laboratory. This method, based on the existing gravimetric method, requires the development of specific measurement and acquisition means.

Previous communications at the International Symposium on Fluid Flow 2018 (ISFFM 2018, see Ref. [3]) and International Congress of Metrology (CIM 2019, see Ref. [4]) presented the state of the art of previous dynamic gravimetric methods, and the first developments of LNE-CETIAT dynamic gravimetric liquid flow primary standard. Moreover, it has been shown in Refs. [5–10] that flow meters response time can cause significant measurement error in the case of fluctuating flow measurement. This article focuses on the new developments and validation of LNE-CETIAT's dynamic standard.

2. Description of the dynamic primary standard

2.1. Working principle

LNE-CETIAT's liquid flow dynamic primary standard is mainly composed of a flow generator, a measuring system, and a dedicated data acquisition and processing software.

The following Fig. 3 presents a general view of LNE-CETIAT's dynamic primary standard.

The following sections describe how each element of the system works.

2.2. Flow generator

Dynamic flow profiles (steps, ramps, or oscillations) are generated using a centrifuge pump associated with flow control valves and fast pneumatic valves. Depending on the need, flow changes can be generated either upstream or downstream of the device under test (DUT). Flow changes within 1 s can be generated within a range from 5 kg/h up to 15000 kg/h. Water temperature is controlled from 12 °C to 90 °C and measured both directly upstream and downstream of the DUT. Pressure upstream of the DUT is controlled within a range of 0.2 barg to 6 barg.

The following Figs. 4 and 5 presents a close-up look on the upstream and downstream flow control systems.

The dynamic flow generator is designed to be a modular and scalable solution. It is made up of the following main elements, in the direction of flow of the fluid (letters in brackets refers to Fig. 4):

- A storage tank (A)
- A pump (B)
- 3 flowmeters associated with 3 electrically controlled control valves, in order to cover the following functional ranges :
  - Low flow line: 1–500 l/h
  - Middle flow line: 60–1800 l/h
  - High flow line: 600 to 15 000 l/h
- 3 pneumatic valves in series with 3 manual control valves directing the flow to the storage tank (D)
- 3 pneumatic valves in series with 3 manual control valves directing the flow to the meter under calibration. Manual control valves allow the pressure drop of the "regulation" and "measurement" loops to be

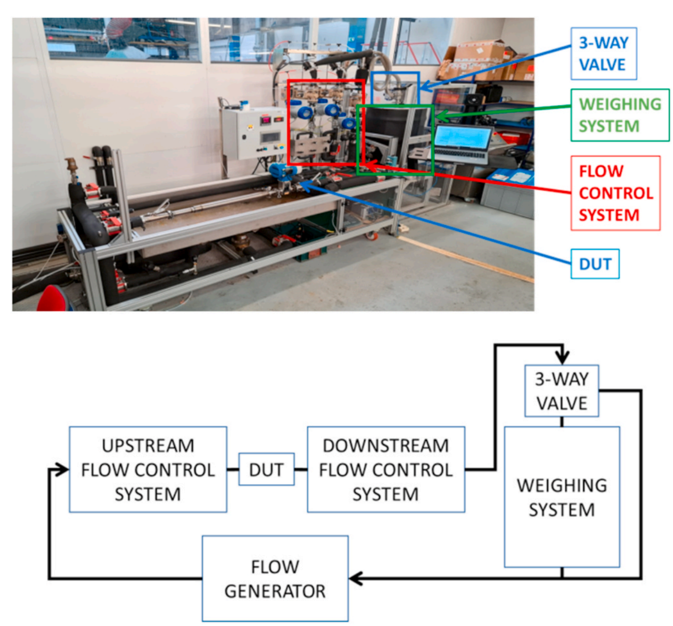


Fig. 3. General picture (top) and schematic (bottom) of LNE-CETIAT's dynamic primary standard.

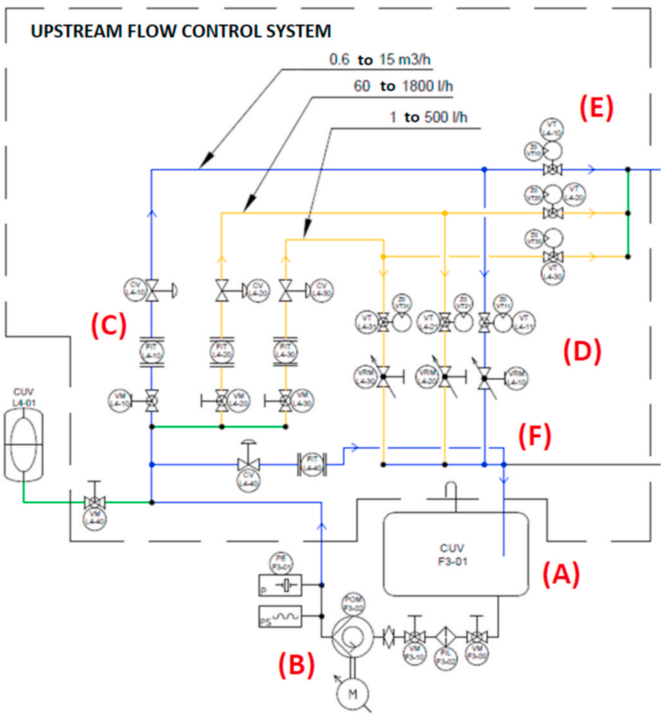


Fig. 4. Schematic of the upstream flow control system.

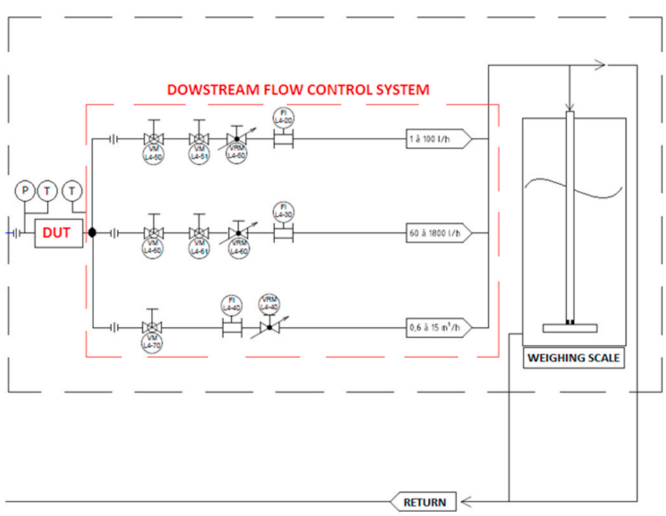


Fig. 5. Schematic of the downstream flow control system.

adjusted taking into account the pressure drop of the meter (s) under test (E)

- A bypass line associated with an electrically controlled regulating valve and a flowmeter to maintain a return flow to the tank in order not to force the use of the pump outside of its nominal operating speed (F)

Both upstream and downstream flow control systems are controlled by an industrial Programmable Logic Controller (PLC) controller that allows to program the desired types of fluctuations, being either steps, ramps, oscillations, or a combination of those, as illustrated in the Fig. 6.

Before an automatic dynamic calibration, an adjustment phase of the flow control parameters of the PLC is necessary, in order to obtain a flow profile closest to the desired one. This phase, called "self-learning", was automated and programmed by LNE-CETIAT. Only the description of the

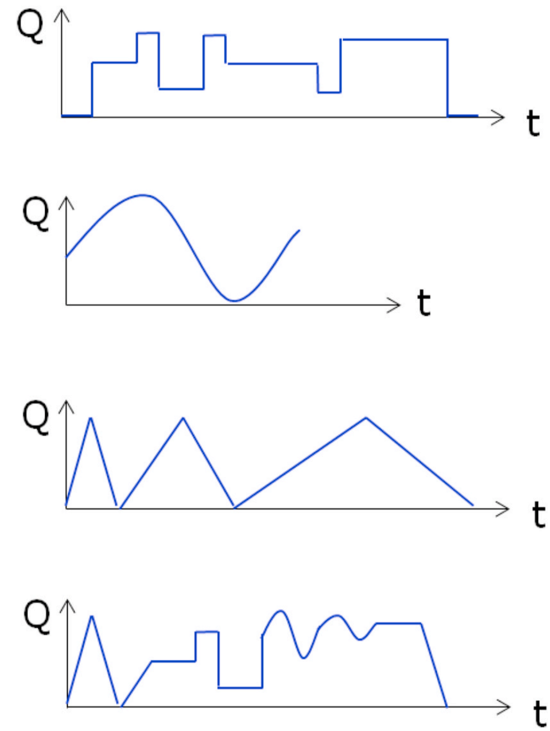


Fig. 6. Types of liquid flow fluctuations which can be generated by LNE-CETIAT dynamic primary standards. From top to bottom: steps, oscillations, ramps, and a combination of these.

desired steps (flow rate, duration, and/or frequency and/or amplitude, and/or speed of ascent/descent) is required and can be carried out directly on a touch screen placed on the front of the bench.

2.3. Measuring system

The dynamic mass flow rate is measured using a Sartorius IS150GG weighing scale (150 kg range, 1 g resolution). The flow is entering the weighing scale's reservoir through an immersed pipe equipped with a deflecting plate, which minimizes the effect of the hydrodynamic jet force towards the weighing scale's plate. When needed, and similarly to the historical static standard described in Refs. [3,4], conversion from reference mass flow rate to reference volume rate is done using the so-called Tanaka's equation for the evaluation of water density, and the measurement of the water temperature using two calibrated Pt100 temperature probee mounted at equal distance upstream and downstream of the DUT. The water density is controlled monthly using an Anton Paar DMA5000 densitometer. This control allows also to calculate the correction factor to be applied to the Tanaka's equation when applied to tap water, as it is the case for LNE-CETIAT. The evaporation of water, within a temperature range of 12 °C–90 °C, has been experimentally evaluated to a maximum of 0.02% of the reference flow rate and taken into account in the uncertainty budget on the reference flow rate.

The dynamic mass flow rate is calculated as the slope of the linear regression on the timestamped mass data, on a sliding time window of 1 s minimum duration, which allows for a quasi-real time reference flow rate calculation, visualization and recording. The mass sampling frequency is 1 kHz, which allows for the calculation of the reference mass flow rate over a minimum of 1 s of mass data, up to several hours depending on the calibration point duration. The time acquisition accuracy and traceability is ensured by the calibration of the sampling frequency using LNE-CETIAT's atomic clock, itself calibrated against the French National Time & Frequency (held by LNE-SYRTE) by the GNSS frames comparison method. This calibration method allows for an accuracy of 1 µs on the time measurement.

The DUT outputs (either pulses, current, voltage, or digital) are synchronized with the reference flow rate, temperature and pressure measurements using a dedicated acquisition system.

The expanded relative uncertainty on the reference flow rate is 0.1% (k = 2) for static (constant) flow, 0.2% (k = 2) for dynamic (fluctuating) flow. As described previously in Refs. [3,4], the uncertainty calculation for the case of dynamic flow is composed of the uncertainty on static flow and the residuals of the linear fit used to calculate the average dynamic flow over the interval of mass data considered, as follows:

$$U_{dynamic,\ k=2} = 2^{*}\sqrt{u_{static}^2 + u_{fit}^2} \quad (1)$$

With u_{static} the uncertainty on static reference flow measurements and u_{fit} the standard deviation of the linear fit residuals [3,4].

The following Figs. 7 and 8 show a picture and a schematic of LNE-CETIAT's dynamic flow measuring system.

2.4. Data acquisition and processing software

The recording of the measured values (mass, pressure, temperatures, and outputs of the device under test) is carried out by a Gantner Instruments QStation T acquisition unit equipped with A101, A107 and A109 cards.

The measurement channels are configured using the Gantner Instruments "Test.Commander" software. The recording, the visualization of measurements in real time, as well as the data processing are carried out by a software produced by LNE-CETIAT, called "EXPERT". This modular and scalable software has been programmed in Python for the interface and in C for the calculations. It makes it possible, among other things, to convert the mass into flow by means of a Kalman filter, filter the data, apply corrections to the measured physical quantities, and correct the response time of the measurement system. The dedicated Kalman filter is also used to denoise the signal whatever the form of the fluctuation (slots, ramps, oscillations). The following figure shows an overview of the EXPERT software user interface.

Fig. 9 shows a general view of the main user-interface of the EXPERT software, which is composed of three areas. The first one allows the user to select the channel to record and display and edit figures. In this first panel (framed in red in Fig. 9), it is also possible to apply filters, corrections factors, and all types of algebraic operations to the selected channels. The second panel (framed in green in Fig. 9), allows for the selection of the parameters used for the automatic detection of plateaus and the subsequent calculations, such as relative errors between two different channels. The third panel (framed in blue in Fig. 9), displays the different channels selected in one or more figures. Within this panel, it is possible to zoom in and out on the curves, place cursors on the curves anddisplay local coordinates, and save the selected figures either to text or comma-separated values (CSV) files or images.

The EXPERT software makes it possible to record and export the processed data, including the mean values, accuracy errors and standard deviations of the device under test. A routine makes it possible, in a few clicks, to automatically detect the flow rate plateaus and to export their mean and standard deviation values, as illustrates in the following Fig. 10.

As shown in the bottom part of Fig. 10, the automatic calculations of averages absolute and relative errors standard deviations are displayed in a dedicated window where the values can either be exported either to text of CSV files. In the top window shown in Fig. 10, the EXPERT software displays a graphical representation of the plateaus with red and blue cursors representing respectively the start and end of each of the detected plateaus.

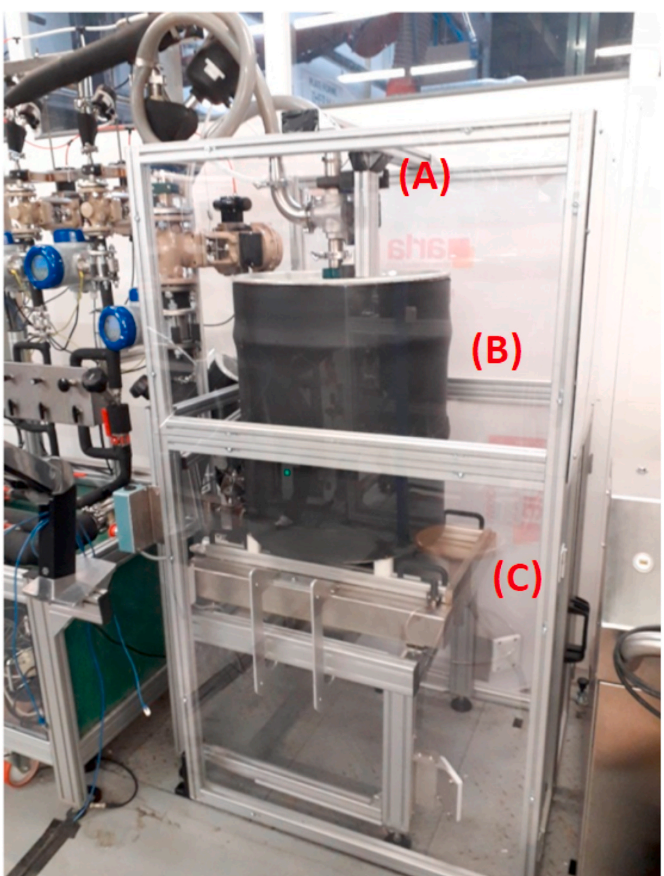


Fig. 7. Picture of LNE-CETIAT's dynamic flow measuring system, showing the three-way valve (A), the collecting vessel (B) and the weighing scale (C).

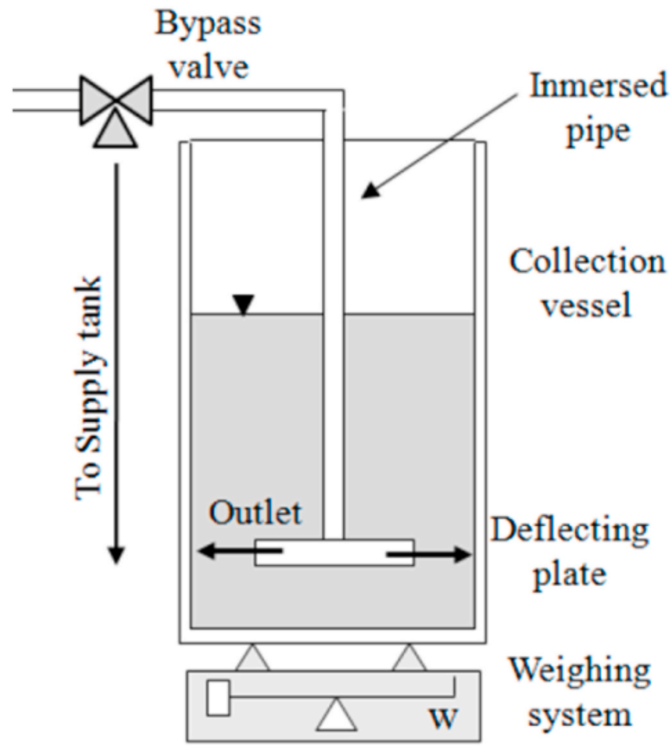


Fig. 8. Schematic of LNE-CETIAT's dynamic flow measuring system.

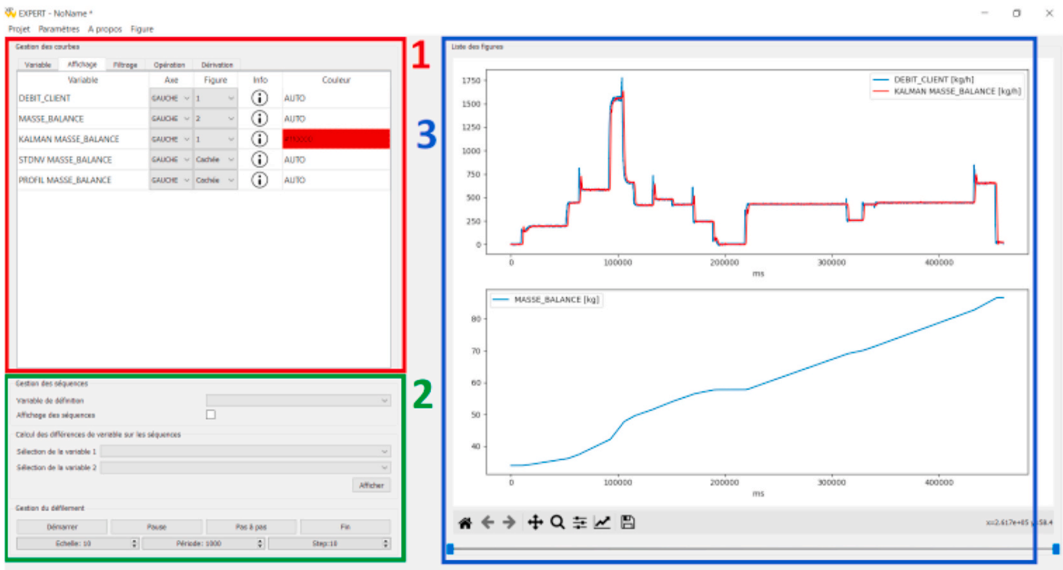


Fig. 9. Overview of the EXPERT software user interface. Area 1 (red): configuration panel. Area 2 (green): automatic detectection of plateaus panel. Area 3 (blue): figures display panel.

3. Validation

3.1. Intra-laboratory comparison for static flows

In order to firstly validate the capabilities of the newly developped standard, an internal comparison of LNE-CETIAT dynamic primary standard has been performed by comparison with the historical macro-flow rates primary standard for static flow rates. The historical French primary standard held by CETIAT has Calibration and Measurement Capabilities (CMCs) for a flow rate range of 8 kg/h to 36 000 kg/h with a best associated relative expanded uncertainty of 0.05% (k = 2), and has been described in details in previous publications [3,4]. The comparison has been performed using a Bronkhorst M14 Coriolis mass flow meter for the flow rate of 30 kg/h, and an Emerson MicroMotion ELITE CMFS150 M Coriolis mass flow meters for flow rates of 2000 to 10 000 kg/h. The degree of equivalence En has been calculated according to Cox [11] and the following equation:

$$E_n = \frac{\varepsilon_{DS} - \varepsilon_{SS}}{\sqrt{U^2(\varepsilon_{DS}) + U^2(\varepsilon_{SS})}} \tag{2}$$

where ε_{DS} is the error of the dynamic standard for a certain flow rate, ε_{SS} is the error of the static standard and $U(\varepsilon_{DS})$ and $U(\varepsilon_{SS})$ are the expanded uncertainties (k = 2) of those values. The (expanded) uncertainty includes the uncertainty in reference flow rate and repeatability. The repeatability is defined as the sample standard deviation of the individual errors for a given flow rate.

The value of E_n has the following meaning:

- The results for a certain flow point are consistent (passed) if $E_n \leq 1$
- The results for a certain flow point are inconsistent (failed) if $E_n > 1.2$.
- For results between $1 < E_n \leq 1.2$ a "warning level" is defined. For this particular situation the particular laboratory is recommended to check the procedures and methodology.

The following Tables 1–3 present the results of the comparison for flow rates from 30 kg/h to 10 000 kg/h.

For flow rates of 5 kg/h and 10 kg/h, an internal comparison of the dynamic primary standard has been performed with the LNE-CETIAT micro flow rates primary standard, which helds CMCs from 1 g/h to 10 kg/h with a best associated relative expanded uncertainty of 0.1% (*k* = *2*), and has been described in details in previous publications [12,13]. The comparison has been performed using a Bronkhorst M14 Coriolis mass flow meter for flow rates of 5 and 10 kg/h. The degree of equivalence has been calculated according to Cox [11].

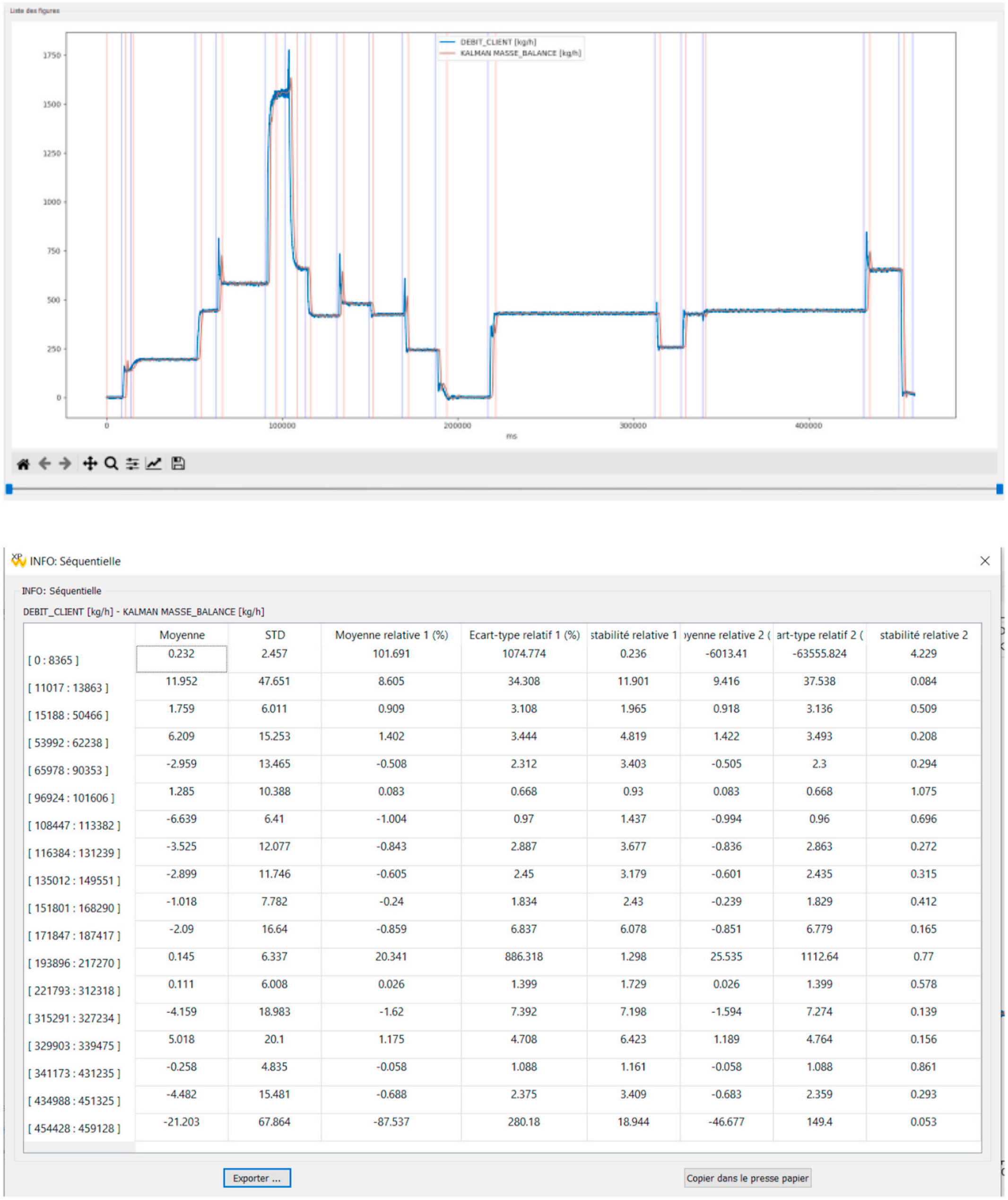
The following Tables 4–6 present the results of the comparison for flow rates from 5 kg/h to 10 kg/h.

All degrees of equivalence obtained for the internal comparison of static flow rates are below one, with an overall relative expanded uncertainty of 0.1% ($k = 2$) for the newly developped dynamic primary standard in static mode (constant flow rates) in a range of 5 kg/h to 10000 kg/h.

3.2. Inter-laboratory comparison for dynamic flows

In order to validate the dynamic generation and measurement capabilities of LNE-CETIAT dynamic primary standard, an inter-laboratory comparison, piloted by LNE-CETIAT, took place in 2020–2021, registered at EURAMET as project n°1506 ″pilot study". The aim of this pilot study is the assessment of the metrological comparability concerning dynamic flow profile capability of the dynamic test rigs in the framework of the EMPIR project 17IND13 Metrowamet - Metrology for real-world domestic water metering. The transfer standard, provided by LNE-CETIAT, consisted of a Pelicase including the following main elements: Emerson MicroMotion Elite CMFS040 M Coriolis Mass Flow Meter, Emerson 5700 Transmitter, Keller PR23 pressure sensor, Rosemount Pt100 Class B HART temperature sensor and was as the transfer standard. The pilot study was performed by means of three flow profiles with volumes of approximately 50 L, 80 L and 100 L simulating dynamic flow load changes in a flow rate range up to 1600 l/h. The following Fig. 11 presents a schematic of the transfer standard package.

The selected flow profiles were determined on the basis of previous studies of consumption data from various apartments and apartment buildings in some European Union (EU) countries. These data were evaluated in relation to flow rates, their durations and speed of flow changes. The flow profiles were chosen with respect to the laboratories capabilities and so that the flow profiles are statistically representative of the actual water consumption in households. Each flow profile represents a different situation, for which the participating laboratory had to demonstrate its capacity to handle different flow profiles. In particular:



	Moyenne	STD	Moyenne relative 1 (%)	Ecart-type relatif 1 (%)	stabilité relative 1	›yenne relative 2 (	art-type relatif 2 (	stabilité relative 2
[0 : 8365]	0.232	2.457	101.691	1074.774	0.236	-6013.41	-63555.824	4.229
[11017 : 13863]	11.952	47.651	8.605	34.308	11.901	9.416	37.538	0.084
[15188 : 50466]	1.759	6.011	0.909	3.108	1.965	0.918	3.136	0.509
[53992 : 62238]	6.209	15.253	1.402	3.444	4.819	1.422	3.493	0.208
[65978 : 90353]	-2.959	13.465	-0.508	2.312	3.403	-0.505	2.3	0.294
[96924 : 101606]	1.285	10.388	0.083	0.668	0.93	0.083	0.668	1.075
[108447 : 113382]	-6.639	6.41	-1.004	0.97	1.437	-0.994	0.96	0.696
[116384 : 131239]	-3.525	12.077	-0.843	2.887	3.677	-0.836	2.863	0.272
[135012 : 149551]	-2.899	11.746	-0.605	2.45	3.179	-0.601	2.435	0.315
[151801 : 168290]	-1.018	7.782	-0.24	1.834	2.43	-0.239	1.829	0.412
[171847 : 187417]	-2.09	16.64	-0.859	6.837	6.078	-0.851	6.779	0.165
[193896 : 217270]	0.145	6.337	20.341	886.318	1.298	25.535	1112.64	0.77
[221793 : 312318]	0.111	6.008	0.026	1.399	1.729	0.026	1.399	0.578
[315291 : 327234]	-4.159	18.983	-1.62	7.392	7.198	-1.594	7.274	0.139
[329903 : 339475]	5.018	20.1	1.175	4.708	6.423	1.189	4.764	0.156
[341173 : 431235]	-0.258	4.835	-0.058	1.088	1.161	-0.058	1.088	0.861
[434988 : 451325]	-4.482	15.481	-0.688	2.375	3.409	-0.683	2.359	0.293
[454428 : 459128]	-21.203	67.864	-87.537	280.18	18.944	-46.677	149.4	0.053

Fig. 10. Automatic detection of plateaus (top window) and export of the corresponding data (bottom window) using LNE-CETIAT "EXPERT" software.

Table 1
Results obtained on LNE-CETIAT's macro-flow primary standards in the scope of the internal comparison of the dynamic primary standard for static macro flow rates.

Average water temperature (°C)	Average water pressure (barg)	Reference mass flow rate (kg/h)	DUT mass flow rate (kg/h)	Average relative error	Relative expanded uncertainty ($k = 2$)
20.4	2.59	29.13	29.10	−0.09%	0.16%
15.1	1.25	2020.51	2021.10	0.03%	0.06%
14.8	1.25	4034.50	4036.47	0.05%	0.05%
14.7	1.25	10044.87	10050.30	0.05%	0.05%

- Flow profile No. 1: starts and ends with a medium flow rate
- Flow profile No. 2: starts with a high flow rate and ends with a medium flow rate

Table 2
Results obtained on LNE-CETIAT's dynamic primary standards in the scope of the internal comparison for static macro flow rates.

Average water temperature (°C)	Average water pressure (barg)	Reference mass flow rate (kg/h)	DUT mass flow rate (g/h)	Average relative error	Relative expanded uncertainty ($k = 2$)
21.2	2.79	30.16	30.12	−0.15%	0.11%
23.3	0.22	1976.02	1974.31	−0.09%	0.10%
23.1	0.40	3993.05	3992.15	−0.02%	0.10%
23.4	2.60	10145.98	10141.39	−0.05%	0.11%

- Flow profile No. 3: starts with a zero flow rate and ends with a medium flow rate.

The following Figs. 12–14 show the aforementioned flow profiles. All participating laboratories were partners of the EMPIR project

Table 3
Degree of equivalence of LNE-CETIAT's dynamic primary standard in the scope of the internal comparison for static macro flow rates.

Mass flow rate (kg/h)	Degree of Equivalence (En)
30	0.30
2000	0.98
4000	0.63
10000	0.84

Table 4
Results obtained on LNE-CETIAT's micro-flow primary standards in the scope of the internal comparison of the dynamic primary standard for static micro flow rates.

Average water temperature (°C)	Average water pressure (barg)	Reference mass flow rate (kg/h)	DUT mass flow rate (kg/h)	Average relative error	Relative expanded uncertainty ($k = 2$)
20.2	1.20	3.58	3.57	−0.24%	0.11%
20.1	4.97	9.99	9.98	−0.11%	0.10%

Table 5
Results obtained on LNE-CETIAT's dynamic primary standards in the scope of the internal comparison for static micro flow rates.

Average water temperature (°C)	Average water pressure (barg)	Reference mass flow rate (g/h)	DUT mass flow rate (g/h)	Average relative error	Relative expanded uncertainty ($k = 2$)
21.2	2.79	4837.18	4837.61	0.01%	0.22%
21.2	2.79	10140.15	10127.78	−0.12%	0.22%

Table 6
Degree of equivalence of LNE-CETIAT's dynamic primary standard in the scope of the internal comparison for static micro flow rates.

Mass flow rate (kg/h)	Degree of Equivalence (En)
5	0.77
10	−0.06

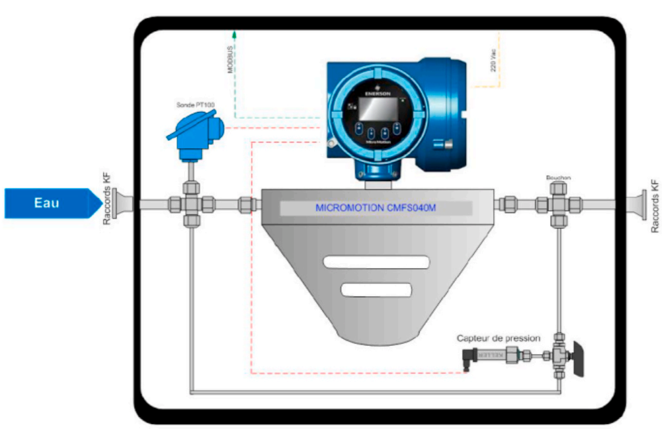


Fig. 11. LNE-CETIAT transfer standard package used for the EURAMET 1506 pilot study.

17IND13 Metrowamet - Metrology for real-world domestic water metering and used their own calibration procedures to calibrate the transfer standard. In Table 7 an overview of the participating laboratories, the type of facility, calibration procedure and references for further reading is given. All laboratories used a dynamic method of

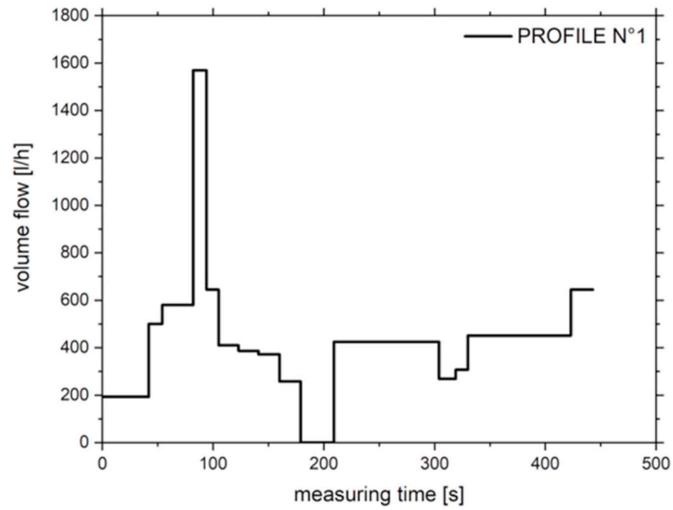


Fig. 12. Flow profile n°1 used for the EURAMET 1506 pilot study.

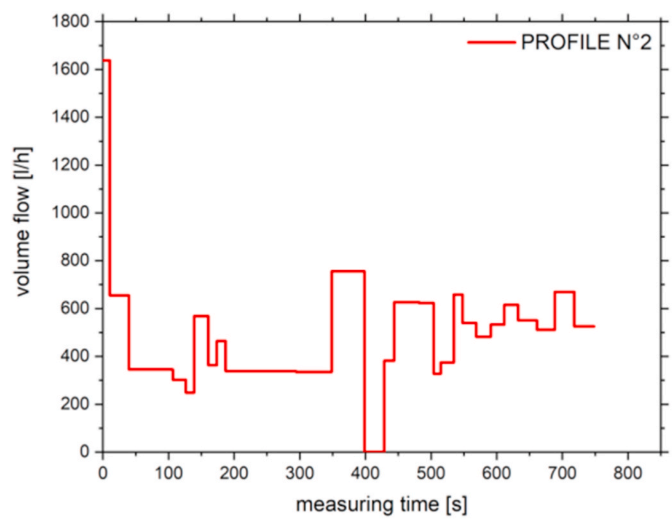


Fig. 13. Flow profile n°2 used for the EURAMET 1506 pilot study.

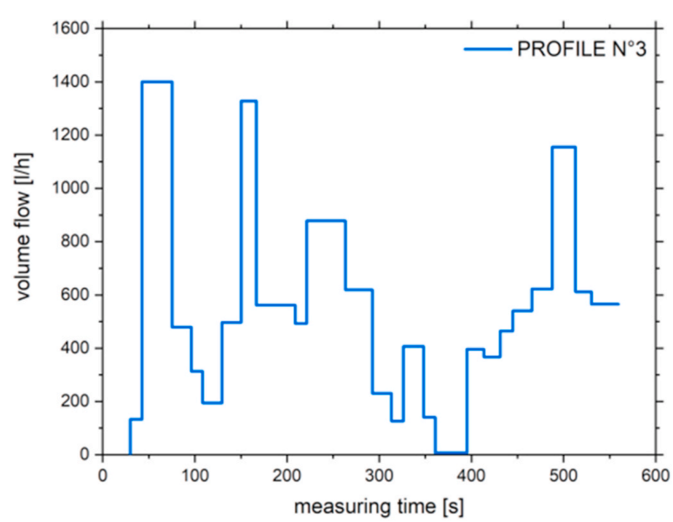


Fig. 14. Flow profile n°3 used for the EURAMET 1506 pilot study.

Table 7
EURAMET 1506 pilot study participants.

Institute	Country	Test rig, method of measurement	Flow profile (No.)	Flow change (s)	Flow change technology
CETIAT (PILOT)	France	Gravimetric with weighing system	1, 2, 3	<1	Fast valves
PTB	Germany	Gravimetric with weighing system	1, 2, 3	<0.1	Critical Nozzles
FORCE	Denmark	Gravimetric with weighing system	2		Fast valves
CMI	Czech Republic	Volumetric with piston prover	1, 2, 3	<0.32	Fast piston position changes
RISE	Sweden	Volumetric with piston prover plus integrated measuring system	1, 2, 3	<0.1	12-bit digital valves
DTI	Denmark	Gravimetric with weighing system	1, 2, 3		Fast valves
VTT	Finland	Gravimetric with weighing system	1, 2, 3		Fast valves
UME TUBITAK	Turkey	Reference flow meter	1		Fast valves

measurement and are independent.

The degree of equivalence has been calculated according to Cox [11]. The following Table 8 and Figs. 15–18 shows the degree of equivalence (En, Fig. 15), and the errors with associated relative expanded uncertainty at $k = 2$ (blue) along with the reference value (red line) and its associated relative expanded uncertainty at $k = 2$ (dashed red lines), Figs. 16–18.

As shown in Figs. 15–18, the relative errors for the three profiles agree within a span of −0.1%–0.2%. All technologies used for the realization of dynamic flows perform similarly. Likewise, all technologies cope similarly well on average with the different profile characteristics. The degrees of equivalence (DoE) observed in this intercomparison show that the test facilities for dynamic liquid flow calibrations of the participating laboratories are in very good agreement.

The participating laboratories state expanded measurement uncertainties of their test facilities between 0.1% and 0.4% ($k = 2$). LNE-CETIAT dynamic primary standard associated relative expanded uncertainty of 0.2% ($k = 2$) is validated by this inter-laboratory comparison for dynamic flow profiles.

The characteristics of the flow profiles produced for this comparison being the most restrictive in terms of the rise and fall times of the flows (less than 1 s), it is expected that the performances and uncertainties associated with the generation of flows in ramps and oscillations, and their combinations, are at the highest level. less of the same order. A fixed value of 0.2% (k = 2) is therefore associated with the dynamic reference flow generated and measured by LNE-CETIAT dynamic primary standard for any fluctuation in the range of the bench's capabilities.

4. Dynamic calibration example

In order to demonstrate the relevance of LNE-CETIAT's dynamic standard and its capability to evaluate experimentally the metrological performances of liquid flow meters under dynamic flow conditions, the following sections present examples of calibration results for a step response (section 4.1) and oscillations (section 4.2).

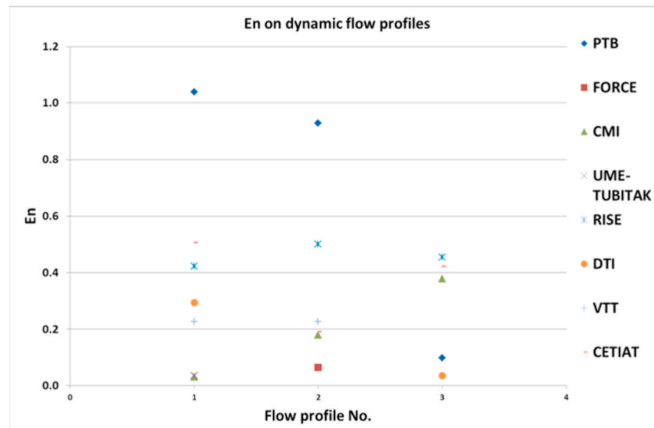


Fig. 15. Graph of EURAMET 1506 pilot study results.

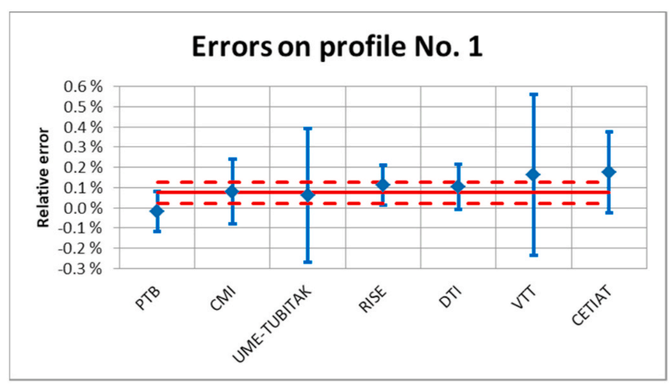


Fig. 16. Graph of EURAMET 1506 pilot study results for profile No.1.

Table 8
EURAMET 1506 pilot study results.

		CETIAT		PTB		FORCE		CMI	
		U(*k* = 2)	En	U(*k* = 2)	En	U(*k* = 2)	En	U(*k* = 2)	En
PROFILE	1	0.20%	0.51	0.10%	1.04			0.16%	0.03
	2	0.10%	0.19	0.10%	0.93	0.10%	0.06	0.22%	0.18
	3	0.18%	0.42	0.10%	0.10			0.16%	0.38
		UME TUBITAK		**RISE**		**DTI**		**VTT**	
		U(*k* = 2)	**En**	**U(*k* = 2)**	**En**	**U(*k* = 2)**	**En**	**U(*k* = 2)**	**En**
PROFILE	1	0.33%	0.04	0.10%	0.42	0.11%	0.29	0.40%	0.23
	2			0.10%	0.50			0.28%	0.23
	3			0.10%	0.45	0.15%	0.04	0.28%	0.46

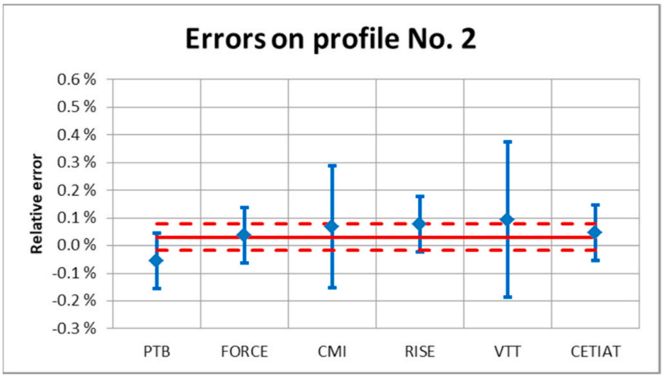


Fig. 17. Graph of EURAMET 1506 pilot study results for profile No.2.

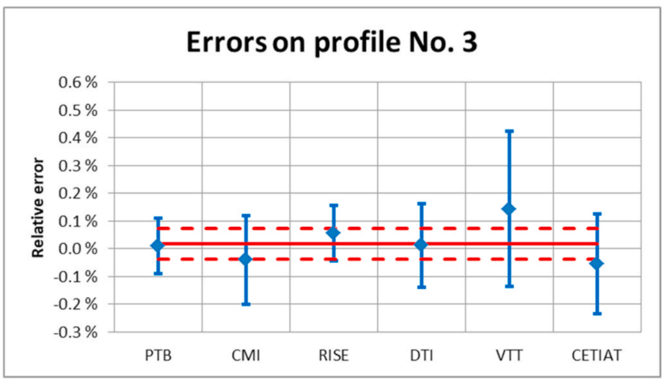


Fig. 18. Graph of EURAMET 1506 pilot study results for profile No.3.

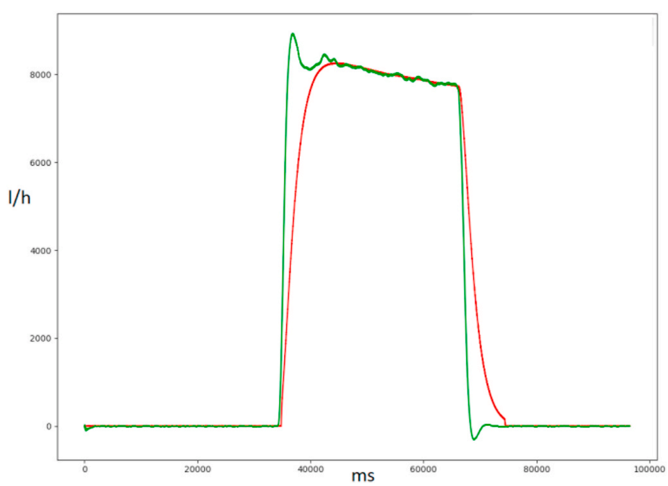


Fig. 19. Step response of an electromagnetic flow meter as measured by LNE-CETIAT dynamic primary standard. Green line: reference flow rate (l/h). Red line: DUT current output (l/h).

4.1. Step response

As an example, the following Fig. 19 shows the flow rates measurement by the dynamic primary standard (green line) and an electromagnetic flow meter analog 4–20 mA output (red line) for a step of zero to about 8000 l/h and a duration of about 30 s.

Using LNE-CETIAT's dedicated EXPERT software, the data acquired and displayed in Fig. 19 have been processed to calculate automatically the following parameters:

$$\text{Dynamic error: } E_{dyn} = \frac{1}{n}\sum_{1}^{n} Q_i^{DUT} - Q_i^{REF} \tag{3}$$

With: Q_i^{DUT} the device under test's flow rate at instant i, Q_i^{REF} the reference flow rate at instant i, $\boldsymbol{n}$ the number of flow samples on the chosen time interval.

$$\text{Relative stability}: \; Stab[\%] = \frac{\sigma_{DUT}}{\sigma_{REF}} \tag{4}$$

With: $\boldsymbol{\sigma_{DUT}}$ the DUT's standard deviation on the chosen time interval, $\boldsymbol{\sigma_{REF}}$ the reference standard deviation on the chosen time interval.

- Response time: duration of the time interval between the instant of the step change of an input variable and the instant when the output variable reaches for the first time a specified percentage of the difference between the final and the initial steady-state value, as defined in entry 351-24-28 of IEC 60050–351:2006 [14].

For the example shown in Fig. 19, the values of the aforementioned parameters are presented in the following Table 9. The response time as been evaluated as the time to reach the target value of 8000 l/h.

As shown by the results obtained and presented in Table 9, the error introduced by the response time of the flow meter in a given period (here, 1 s sliding time period), called dynamic error, is significantly increased in the case of a step flow: a factor of ten degradation of the relative error can be shown for the experimental example described above. The response time of the DUT induce a delay and filtering on the flow rate measurements. The longer the response time, the more it will have a negative impact on the dynamic error in the case of aperiodic fluctuation. This error can be reduced by reducing the DUT time response, for example, by reducing the so-called "time constant" or "averaging period" of the flow meter. Further studies should be performed in order to quantify the degree of improvement on metrological performances of flow meters, gained by reducing the time response, and compared to other devices and flow measurement principles.

4.2. Oscillations

As an example, the following Fig. 20 shows the flow rates measurement by the dynamic primary standard (green line) and an electromagnetic flow meter analog 4–20 mA output (blue line) for oscillations of:

- Amplitude = 0–4500 l/h, frequency = 0.1 Hz, duration = 50 s.
- Amplitude = 1500–2500 Hz, frequency = 0.5 Hz, duration = 30 s.

Using LNE-CETIAT's dedicated EXPERT software, the data acquired and displayed on Fig. 20 has been processed to calculate automatically the following parameters: dynamic error and relative stability (as defined in paragraph 4.1), and phase shift between the reference signal and the DUT.

Results presented in Table 10 show the effect of an increasing oscillation frequency on the DUT's metrological performances: its relative error doesn't evolve, but its relative stability decreases as the amplitude is dampened, and the output signal phase shifts compared to the phase of the reference flow rate.

Table 9
Step response results of an electromagnetic flow meter as measured by LNE-CETIAT dynamic primary standard.

Parameter	Total step 0->8000 l/h -> 0	Steady flow (8000 l/h)
Relative error	−0.60%	−0.06%
Relative stability	92.15%	102.08%
Response time (s)	5	Not applicable

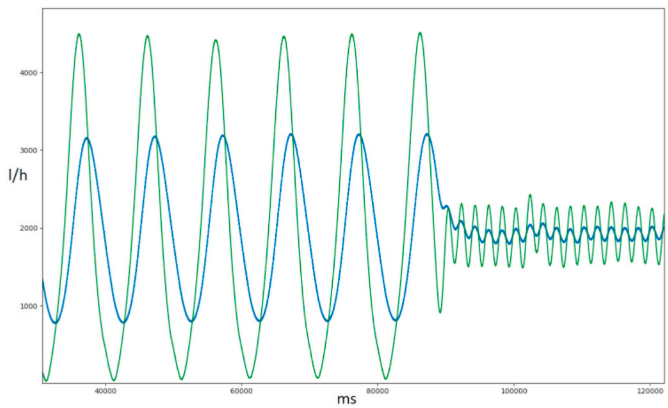


Fig. 20. Oscillations response of an electromagnetic flow meter as measured by LNE-CETIAT dynamic primary standard. Green line: reference flow rate (l/h). Blue line: DUT current output (l/h).

Table 10
Oscillation response results of an electromagnetic flow meter as measured by LNE-CETIAT dynamic primary standard.

Parameter	Oscillation frequency 0.1 Hz	Oscillation frequency 0.5 Hz
Relative error	−0.14%	0.09%
Relative stability	55.83%	24.21%
Phase shift (deg)	36° (10% of 360°)	342° (95% of 360°)

5. Conclusion

As part of its mission of French national standard for liquid flow, and in the scope the EURAMET EMPIR Metrowamet project, LNE-CETIAT has developed and validated a primary standard composed of a dynamic flow generator and a dynamic gravimetric measurement system.

The flow generator is composed of two flow control systems, allowing a generation of steps, ramps, and oscillations, either by controlling the flow upstream or downstream of the device under test. The flow control systems are based on fast pneumatic valves along with control valves which are piloted by a PLC programmed by LNE-CETIAT.

The data acquisition system is composed of a fast and synchronous sampling station, for the primary standard measurands (mass, pressure, temperature) and the device under test output(s). The EXPERT software developed by LNE-CETIAT allows piloting, visualization, and processing of all measurement channels. Its functionalities include automatic detection of steps and calculation of the device under test's metrological parameters such as its relative error and stability. A dedicated Kalman filter is used to denoise the signals and calculate the reference mass flow based on the raw dynamic mass measurements.

The validation of LNE-CETIAT dynamic primary standard has been performed by intra- and inter-laboratory comparisons, the later being registered as EURAMET Pilot Study No.1506, and piloted by LNE-CETIAT which provided the transfer standard package. All results obtained showed good agreement with the primary standard relative expanded uncertainty of 0.1% ($k = 2$) for steady flows and 0.2% ($k = 2$) for unsteady flows.

Finally, first dynamic calibrations of flowmeters demonstrated the capabilities of LNE-CETIAT primary standard for the metrological assessment of response time, dynamic error and relative stability of flow measuring devices.

Author statement

Florestan Ogheard: writing, reviewing and editing. Jean Noël: software. Pascal Granger: software. Carl-André Gassette: software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] https://www.ptb.de/empir2018/metrowamet/the-project/.
[2] https://www.euramet.org/technical-committees/tc-projects/details/project/validation-of-standards-for-liquid-flow-rate-under-dynamic-flows/?tx_eurametctcp_project%5Baction%5D=show&tx_eurametctcp_project%5Bcontroller%5D=Project&L=0&cHash=3955aa5dd42587cb6cbb75031c572c99.
[3] F. Ogheard, First Steps toward Dynamic Reference Calibration Methods for Liquid Flow Meters at LNE-CETIAT, 10th ISFFM, Querétaro, Mexico, 2018.
[4] F. Ogheard, Development of a Dynamic Gravimetric Calibration Method for Liquid Water Flow Metering, International Congress of Metrology, Paris, France, 2019.
[5] D. Wiklund, M. Peluso, Flowmeter Dynamic Response Characteristics Part 1: Quantifying Dynamic Response, Rosemount, Inc., Chanhassen, MN, 2002.
[6] D. Wiklund, M. Peluso, Flowmeter Dynamic Response Characteristics Part 2: Effects in Various Flow Applications, Rosemount, Inc., Chanhassen, MN, 2002.
[7] J.J. Aguilera Mena, Dynamic Weighing Calibration Method for Liquid Flowmeters – A New Approach, Thesis dissertation, Braunschweig, 2012.
[8] I. Shinder, I. Marfenko, NIST Calibration Services for Water Flowmeters, NIST Special Publication 250, National Institute of Standards and Technology (NIST), Gaithersburg, MD, August, 2006.
[9] J. Pope, et al., NIST's Fully Dynamic Gravimetric Liquid Flowmeter Standard, 9th International symposium on fluid flow measurement, Arlington, VA, USA, 2015.
[10] I.I. Shinder, et al., Accurately measuring unsteady water flow using a dynamic standard, Proc. of Meas. Sc. Conf. (2009) (Anaheim).
[11] M.G. Cox, Evaluation of key comparison data, Metrologia 39 (2002) 589–595.
[12] F. Ogheard, et al., Recent Improvements of the French Liquid Micro-flow Reference Facility, Measurement Science and Technology, vol. 29, Congrès International de Métrologie, CIM 2017. Number 2.
[13] F. Ogheard, Validation d'un banc d'étalonnage primaire en microdébitmétrie liquide et application aux dispositifs médicaux de perfusion, REVUE FRANÇAISE DE MÉTROLOGIE n°42 2 (2016).
[14] Entry numbered 351-24-28 in IEC 60050-351. https://www.electropedia.org/iev/iev.nsf/display?openform&ievref=351-45-36, 2006.